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The quest for sustainable forest bioenergy: win-win solutions for climate and biodiversity

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ABSTRACT

The debate on forest bioenergy sustainability has been so far dominated by assessments made through the carbon emissions lens. The biodiversity perspective has been largely missing. The European Green Deal's ambitious targets have brought biodiversity and ecosystem condition restoration and conservation to the core of the EU's legislative portfolios. An opportunity to revisit some important governing texts with a biodiversity lens has therefore presented itself.

In this study, we review the impacts on biodiversity and carbon emissions of specific bioenergy pathways that may be used to supply additional forest-based energy. We then synthesize our findings in a nexus matrix, plotting the pathways along a gradient of benefits through to detriments on the two dimensions to highlight win-win and lose-lose options.

We found that some pathways do mitigate carbon emissions in the short-term while not deteriorating ecosystem condition. These include collecting fine woody debris within limits of locally established thresholds. We highlight the pathways that do little to mitigate carbon emissions and that are detrimental to ecosystems as well. These include removal of coarse woody debris and low stumps or the conversion of semi-natural, primary and old-growth forests to plantation forests with the purpose to produce bioenergy.

We conclude that in the currently polarised debate an approach which unambiguously eliminates negative options is more fruitful than trying to find agreement on best options. Consequently, we present several governance measures that could limit the uptake of clearly undesirable pathways within Europe and we show that some lose-lose pathways are still considered "sustainable" within the European Green Deal.

1. Introduction

Wood-based[1] bioenergy currently constitutes the largest renewable energy source in the EU-27 + UK, contributing to 43% of the inland consumption of renewable energy in 2017 [1]. Projections from the European Commission show that bioenergy production is expected to increase by 25% by 2030, and to more than double between 2015 and 2050, with the use of forest biomass for energy expected to increase by 47% by 2050 [2].

The environmental sustainability of forest bioenergy is the subject of a lengthy scientific and societal debate [3–13] that has highlighted the strong differences in attitudes, beliefs, and priorities among actors on how forest resources should be managed and utilized [14,15]. Results on the specific extent and role of wood-based energy in climate change mitigation differ widely in the scientific literature, ranging from studies concluding that forest bioenergy increases GHG emissions compared to fossil fuels over a timescale of decades, centuries, or even indefinitely (e.g. Refs. [16–18]), to others concluding that significant emission reductions can be achieved within reasonably short timeframes (e.g. Refs.

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[1] "Wood-based bioenergy" refers to all energy forms produced from any woody biomass feedstock, obtained directly or after processing, irrespective of the specific origin of the wood (e.g. forests, other wooded lands, short rotation coppices on agricultural land etc …). In this manuscript we focus solely on energy produced from wood obtained, directly or after processing, from forest land, henceforth 'forest bioenergy'.

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Acronyms

BECCS	Bioenergy with Carbon Capture and Sequestration
CWD	Coarse Woody Debris
EGD	European Green Deal
EU	European Union
FSC	Forest Stewardship Council
FWD	Fine Woody Debris
IAMs	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IRW	Industrial RoundWood
LCA	Life Cycle Assessment
MAES	Mapping and Assessment of Ecosystems and their Services
OWC	Other Wood Components
PEFC	Programme for the Endorsement of Forest Certification
SM	Supporting Material

[19–21]). This divergence cannot be pinpointed solely to the use of a specific type of forest biomass, e.g. logging residues vis-à-vis roundwood, but rather to different assumptions on counterfactuals, market-mediated effects, and forest management practices considered [12,16,21–23].

However, while bioenergy is promoted mainly as a climate change mitigation strategy despite these divergent results, the IPCC and IPBES alike [24,25] have shown that large-scale deployment of bioenergy may have significant negative impacts on local biodiversity and ecosystems. This is especially worrying because an increased demand for wood for bioenergy could exacerbate pressures on forest ecosystems, which are under increasing strain due to both direct or indirect anthropogenic stressors, such as pollution, persistent human interventions, and climate change [25–28]. The MAES (Mapping and Assessment of Ecosystems and their Services) study [26,28] states that EU forests show some encouraging trends in relation to area coverage and growing stock, albeit the carbon sink shows a decresing trend. However, pressures such as acidification, eutrophication, drought, warming, and tree cover loss remain high. As a result of these pressures, forest condition is undermined and is, on average, degrading. Additionally, the Habitats Directive assessment of the conservation status of forest habitats [29] concludes that the conservation status of the forest habitats and species listed in the Habitats Directive is generally poor with little progress towards good status, and that forestry activities are the dominant pressure reported for most of the forest habitat types.

Recent political developments in the EU, such as the European Green Deal (EGD) [30], the 2030 Biodiversity strategy [31] and the first European Climate law setting a mandatory net-zero GHG emissions target by 2050 [32], as well as prominent initiatives from civil society, such as the Global Goal for Nature to halt biodiversity loss by 2030 [33,34] and the Leaders' pledge for nature [35], acknowledge that sustainable energy sources in the Anthropocene must, as a bare minimum, achieve climate change mitigation without negatively affecting biodiversity (the EGD 'Do no harm' principle). Within this political context, as the European Commission has tabled its proposals to achieve the EGD objectives (i.e. the "Fit for 55 package" [36]), a window of opportunity has opened to re-assess the role of forest bioenergy within EU climate and energy policies and to re-define the boundaries of sustainable forest bioenergy use, with a stronger focus on biodiversity protection [37].

There are many alternative paths to achieve climate neutrality, even with low or no bioenergy use [38–40], but only healthy and biodiverse, resilient, forests can supply ecosystem services in the long run. It follows that any bioenergy demand must be supplied through pathways that provide win-win solutions for climate and biodiversity. The first crucial step is thus to identify such pathways, even though this information is not yet readily available. For instance, Agostini et al. [23] found that only 3 out of the 100 most cited Life Cycle Assessment studies on bioenergy had analysed impacts on biodiversity. This gap is likely due, at least in part, to the lack of an established and widely accepted quantitative methodology to capture impacts on the multiple attributes of biodiversity and of ecosystems' condition [41].

With this paper we contribute to filling this gap by evaluating the climate-biodiversity nexus for several forest bioenergy pathways. Despite the lack of specific focus on biodiversity within bioenergy literature, the ecological literature has a wealth of information on the potential impacts of different forest management practices on forest ecosystems. Therefore, we rely on a literature review and qualitative knowledge synthesis as a first step of our analysis. Specifically, we investigate the impacts of different pathways derived from three possible interventions that could be driven, directly or indirectly, by an increase in bioenergy demand: i) increased removal of logging residues, ii) afforestation, and iii) conversion of primary and semi-natural forests to plantation forests. We then evaluate the carbon impact of these same pathways, and we synthesize our findings in a matrix identifying win-win and lose-lose options. Finally, this paper expands on the analysis originally described in Camia et al. [42] by comparing our findings with the recent EU Commission 'Fit for 55' legislative proposals [36].

The structure of the paper is as follows: Section 2 presents a detailed description of the assessment structure and method as well as a description of the main delimitations and assumptions of the study; Section 3 presents a narrative literature review and the qualitative impact assessment for each pathway; Section 4 discusses the final synthesis of biodiversity and climate impacts for each pathway, identifying win-win and lose-lose options; Section 5 draws conclusions, evaluates the policy implications of our findings, and proposes future research lines.

2. Assessment approach, scope, and methods

Fig. 1 illustrates the conceptual approach of the assessment. Following a cause-effect chain approach, we first present bioenergy as a part of the broader forest sector thereby distilling the main responses of the sector to an increased demand of wood for bioenergy. Among those responses, we select three interventions that put direct pressure on forest ecosystems and biodiversity. To capture the differential impacts of each intervention in more detail, we disaggregate each intervention into specific pathways.

Once the pathways are identified and defined, we deal with the assessment of each pathway. Firstly, we provide a qualitative assessment method to evaluate the potential impacts on biodiversity and on carbon emissions, including the selection of relevant impact categories that are specific for each intervention. We then evaluate the impacts on all selected impact categories for each pathway. Finally, we present the synthesis of the assessment into a matrix of trade-offs between climate change and biodiversity impacts.

2.1. *Definition of interventions and pathways*

2.1.1. *Bioenergy in the forest sector*

Fig. 2 illustrates wood flows in the forest-based sector, in line with the wood flows in Cazzaniga et al. (2019) [43]. Wood is removed from the forest through silviculture operations producing logs of different qualities and for different uses. Wood processing industries then transform the logs into main products (i.e. sawnwood, wood-based panels, wood pulp) and secondary co- and by-products (i.e. chips, sawdust, bark, and black liquor). The products generated are used for material end-uses that fulfil functions in the economy and can replace non-woody materials, including fossil-based and high energy intensity materials. Primary wood from silviculture (e.g. fuelwood), or wood from

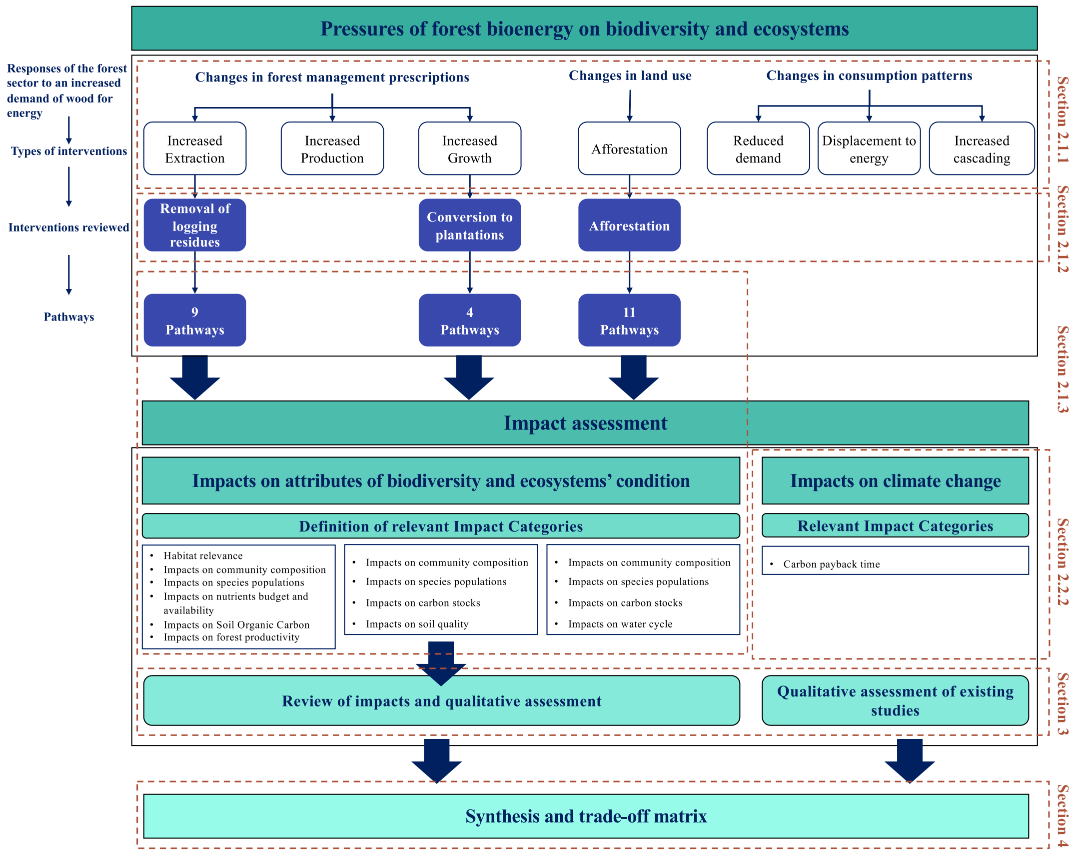

Fig. 1. Scheme of the impact assessment of forest bioenergy pathways on biodiversity, ecosystems, and climate change.

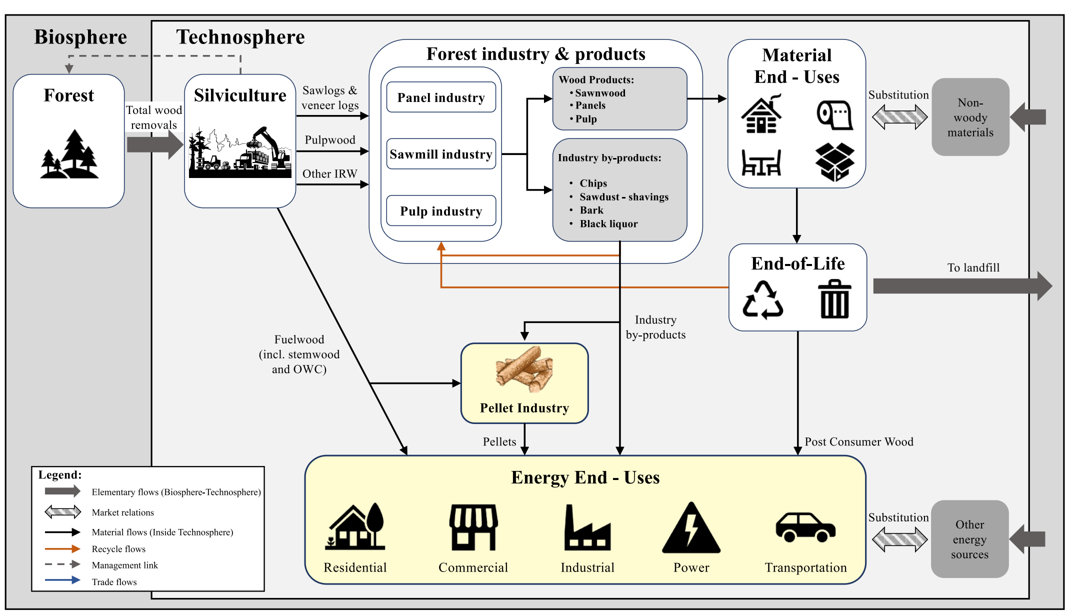

Fig. 2. Schematic of wood flows across the forest sector. Wood is harvested from the forest (on the left) and then used within the technosphere according to the various quality of the biomass harvested, to produce both materials and energy. The figure displays different types of links between the sectors: material flows are indicated by black arrows, by orange arrows (for recycle flows), by blue arrows (for trade flows), or by thick grey arrows for elementary flows between the biosphere and technosphere. Non-material links are also indicated: thick striped double arrows indicated market-mediated relations, the dashed grey arrow represents the forest management.

secondary (e.g. sawdust) or tertiary (e.g. recovered post-consumer wood) sources, are used for heat or electricity production in various sectors. Market-mediated effects take place within the material and energy sectors, so that the production of wood-based materials or bioenergy might increase and potentially substitute non-woody materials or other energy sources, respectively. Quantifying the flows and feedstocks of wood used for energy in EU-28 in 2015, Camia et al. [42] found that 37% was derived from primary feedstocks (i.e. industrial roundwood and fuelwood), 49% from secondary and tertiary sources, and another 14% from uncategorized sources.

When assessing the impact of an increased penetration of forest bioenergy on biodiversity and on climate change we must therefore consider the dynamics of the whole forest sector [44]. Giuntoli et al. [12] presented a framework for classifying the potential responses of the forest sector to an increased demand of wood for energy into three categories affecting: 1) forest management practices, 2) land use, or 3) consumption patterns. The first group of responses concerns forest management practices and their consequences on in-situ carbon stock and sink, and on local biodiversity. Examples of this response type include interventions such as the removal of logging residues, increasing pre-commercial and commercial thinning intensity, and intensifying the final harvest intensity on commercial stands by shortening harvest rotations. Additionally, interventions can take place with the aim of improving a forest's wood productivity, for instance: applying fertilization, shifting to fast-growing plantations, tree breeding, and restoring degraded or abandoned stands. The second response type assumes that forest bioenergy demand may impact land-use and stimulate interventions such as afforestation. The last response concerns changes in the consumption patterns of wood products, but it is not developed further in this article since it does not relate directly to forest management and land-use change and therefore cannot be connected to direct impacts on biodiversity.

2.1.2. *Definition of interventions assessed*

Large-scale integrated assessment models (IAMs) are often utilized to capture the impacts of future policy scenarios on energy systems and on the climate [24,25,45]. However, due to the global scale and approach of these models, they are unable to represent the diversity of the possible responses described above and their relevant impacts. IAMs often only account for the coarse impacts associated with land use (land cover) changes, and only focus on a small set of biodiversity attributes [46], exemplified by the use of the Potentially Disappeared Fraction (PDF) of global species [2,47]. Although new and more refined methods are being developed [48], these still capture mainly the impacts of land transitions.

The EU Renewable Energy Directive [49] prescribes criteria that forest bioenergy must comply with in order to be considered 'sustainable' and to count towards national renewable energy targets. These sustainability criteria aim to ensure compliance with sustainable forest management laws and principles (i.e. legality, regeneration, protection of sensitive areas, minimization of biodiversity impacts; and maintenance of the long-term forest productivity). These criteria address very specific details of forest management that are not yet captured through global and system-level models. Therefore, following a product-perspective borrowed from Life Cycle Assessment, and according to the forest sector dynamics mentioned in section 2.1.1, we design and select individual supply chain pathways representing specific forest management and land use interventions that can thus be assessed independently from the rest of the system. Through this perspective we can provide informed recommendations for forest management that can be used by decision makers to promote bioenergy options that are beneficial both to biodiversity and climate change mitigation, and to avoid those that are detrimental to one, the other, or both. Among all possible responses of the forest sector to an increase in wood for bioenergy demand, we selected the following three specific interventions:

1. Removal of different types of logging residues;
2. Afforestation of different types of non-forest land with different types of forests;
3. Conversion of primary and semi-natural forests into plantation forests.

Giuntoli et al. [12] found that removal of logging residues has likely been driven by bioenergy demand at least in Canada and Sweden, and that conversion of semi-natural forests to plantation forests might have been partially driven by bioenergy demand in the US Southeast. On the other hand, there was no strong evidence of afforestation resulting from bioenergy expansion. Nonetheless, all three interventions are still high on the agenda of potential climate change mitigation strategies [2,24] and could take place as a direct or indirect effect of increased demand of forest biomass (incl. for bioenergy). Furthermore, we analyse these interventions because they aim to supply 'additional' biomass [50,51] above the current provision, i.e. biomass that, in the absence of an increased bioenergy demand, would not have been produced (through afforestation or conversion to plantations with higher productivity) or would have remained in situ to decompose or burn (logging residues) [52].

We do not claim that these interventions cover the majority or the most likely ones to take place because of an increased demand of bioenergy in Europe, however we excluded other interventions for several reasons. Firstly, because many of the interventions excluded are part of more 'traditional' forest management practices that have already been the subject of extensive research (see e.g. Ref. [53]). Secondly, they may rather rely on simply increasing extraction levels (e.g. shortening rotations) or on displacing materials from other sectors. In the case of increased extraction levels, the impacts on atmospheric carbon are known to be adverse in most cases (see Ref. [16]), thus there was not much added value in looking at potential trade-offs. In the case of market displacement, indirect effects are very important and therefore would warrant a different type of analysis, looking in depth at market-mediated effects [54].

2.1.3. *Description of pathways and relevant impact categories*

2.1.3.1. Removal of logging residues. Wood that is left in the forest after forestry logging operations is commonly referred to as logging residues. These materials generally include woody debris from final felling (e.g. branches, leaves, stumps, roots, tops, bark), small trees from thinning and clearing operations, and generally unmerchantable stem wood [55].

The specific definition of which materials constitute 'logging residues' is important, because different types of deadwood play different ecological roles and, consequently, specific impacts are associated to their removal. We focus here only on woody debris produced during final felling and we differentiate among the following three types of residues, highlighted in Fig. 3:

- Fine Woody Debris (FWD) (including slash, i.e., tops, branches, twigs, leaves and needles);
- Coarse Woody Debris (CWD) (including snags, standing dead trees, and high stumps);
- Low-stumps and roots.

Concerning the role of these feedstocks for bioenergy, Camia et al. [55] showed that, on average, 65 Mm^3/year (13% of total removals) of

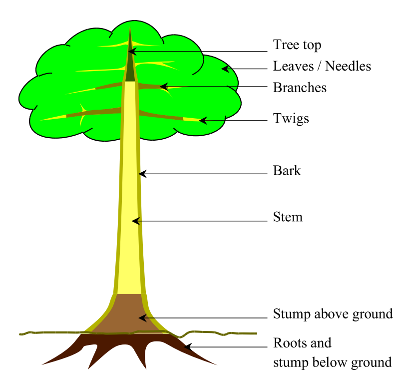

Fig. 3. Parts of a tree from a commercial logging perspective.

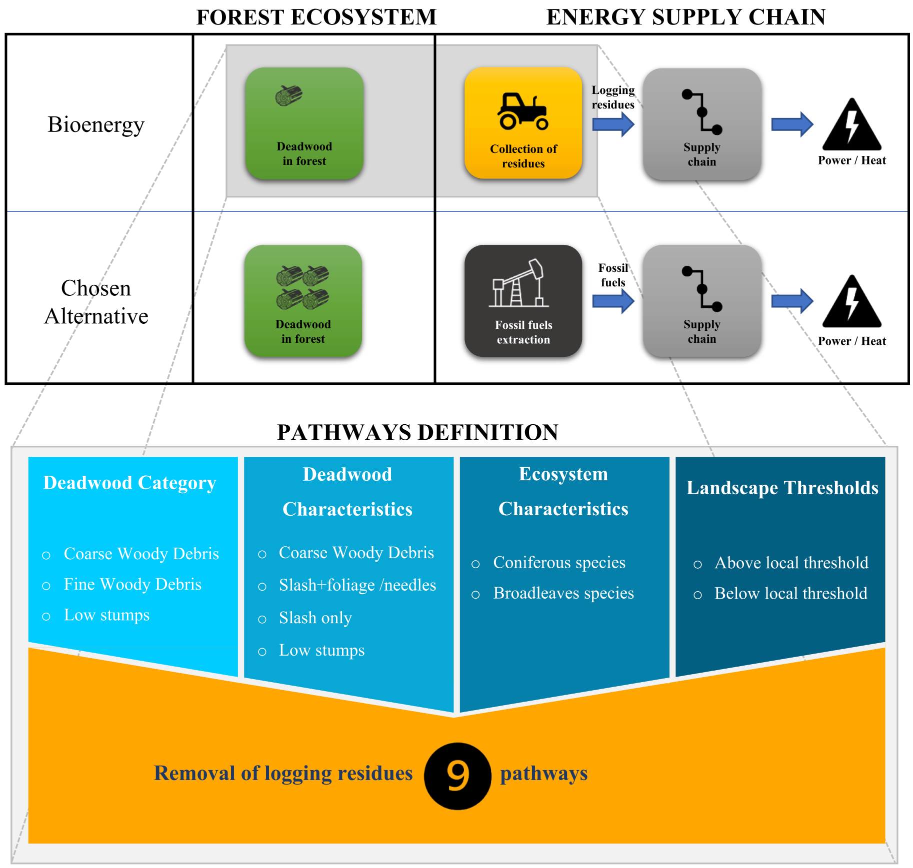

Fig. 4. Supply chain and counterfactual for the production of energy from intervention 'removal of logging residues'. The magnifying panel illustrates the main factors through which 9 archetypical pathways are defined.

other wood components (OWC, i.e. wood that is not stem) was removed in the EU-28 in the period 2004–2013, and the European Commission's climate and energy modelling exercise indicates that, in 2015, forest residues accounted for 14 Mtoe, or 10% of all bioenergy feedstocks in the EU-27.

Fig. 4 defines the various processes constituting the bioenergy supply chain and its chosen alternative scenario, i.e. "the hypothetical situation without the studied product system" [56]. For this intervention we assume that without the increased demand for bioenergy the logging residues would have remained in the forest as deadwood. The importance of the choice of alternative scenarios for energy supply is instead discussed further in section 2.2.2. The supply chains are subdivided in processes taking place in the forest ecosystem and processes required to produce energy. In fact, our assessment focuses solely on the impacts of changes of forest management and land use since this step in the supply chain impacts ecosystems and biodiversity directly and to the highest extent. Pollutants' emissions along the rest of the supply chain can also affect biodiversity and ecosystems by causing acidification and eutrophication. However, while these impacts can be important for bioenergy pathways and often relatively even higher than fossil fuels [57], they are out of the scope of our analysis which aims to support decision makers in defining sustainable forest management criteria for the promotion of win-win bioenergy pathways. Supply chain emissions are regulated within the realm of transport and industrial pollution policy. The magnifying panel in Fig. 4 shows the multiple factors considered when disaggregating this intervention into specific pathways. Through the combination of these factors, nine archetypical pathways are defined (Table S3).

While these materials are considered 'residues' from an economic perspective, deadwood plays a key role in forest ecosystems functions and its removal can lead to several detrimental impacts. Deadwood extraction causes impacts linked both directly to the removal of the biomass material and to the disturbances caused by the mechanical operations (Figure S2). These in turn lead to three main impacts affecting various attributes of ecosystem condition: i) losses of nutrients, affecting the overall budget and physico-chemical availability of nutrients in forest soils; ii) changes in soil organic carbon content; iii) reduction in deadwood quantity and diversity due to substrate loss and destruction.

These latter changes in deadwood quantity and quality will affect both saproxylic[2] and non-saproxylic species proportionally to the relevance of the habitat affected. Deadwood removal, in fact, can negatively affect saproxylic biodiversity by removing a primary source of nutrition for the saproxylic food web [58] and potentially reverberating up the food chain [58–60]. Additionally, decaying deadwood provides habitats for nesting of insects, birds, and mammal species, and epixylic lichens and mosses use deadwood as a substrate for growth.

Saproxylic species are already a highly threatened taxonomic group, mainly due to the shift towards intensive commercial forestry which has modified forest ecosystems, reducing old and veteran trees, and drastically reducing the amount and diversity of deadwood across managed forests (either through active removal of residues, salvage logging, and through site preparation techniques, which are destructive to legacy structures) [61,62]. Saproxylic species have an essential role in nutrient cycling (mineralization and humification) by decomposing deadwood

[2] Stokland et al. [58] define the term saproxylic as "any species that depends, during some part of its life cycle, upon wounded or decaying woody material from living, weakened or dead trees".

and returning macro and micro nutrients minerals to the soil, making them available for new growth [59,63]. This may negatively affect the overall productivity of the forest and a whole range of associated ecosystem services.

Based on these considerations, the impact categories presented in Table S4 were selected to evaluate the outcomes of the removal of logging residues found in the literature.

2.1.3.2. Afforestation[3]. Griscom et al. [64] examined how nature could contribute to climate change mitigation. They presented a comprehensive analysis of what they termed "natural climate solutions" (NCS) (also referred to as nature-based solutions): 20 actions for conservation, restoration, and/or improved land management that would increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural ecosystems. Afforestation and tree planting operations appear as important components of NCS, mitigating climate change by increasing the C-stock in the biosphere and producing wood for materials and energy, while at the same time restoring habitats and thus improving ecosystems' condition.

This narrative is widespread, from biodiversity policies and strategies [31], to climate change mitigation options assessments [65], and certainly within bioenergy literature [12]. However, recent evidence indicates that when environmental criteria are not adequately addressed, tree planting may actually worsen the condition of ecosystems. Ecosystem conditions can change significantly as in most cases afforestation involves transforming open-space ecosystems into closed-canopy forests. Other potential trade-offs (e.g. with food security) have also been highlighted [24]. Therefore, afforestation interventions should be subjected to similar deep scrutiny applied to other land use and land cover changes [66,67].

Fig. 5 illustrates the supply chain for bioenergy production from afforestation, as well as its counterfactual, in which we assume that the former land use (e.g. pastureland, cropland, grassland) remains unaffected. The magnifying panel illustrates the five main factors whose combination produces the eleven archetypical pathways defined for this intervention (Table S3). We can group the pathways into two main typologies: afforestation with intensive monoculture plantations and afforestation with mixed species (polycultures), native species, and low intensity management. We analyse the impacts of all the pathways, albeit when afforestation is driven simply by market forces - such as an increase in bioenergy demand – without conditional requirements, it is more likely that productivity becomes the main goal for the new forest land and that monocultures are thus favoured [68]. The selected impact categories for this intervention are reported in Table S4.

2.1.3.3. Conversion to plantation forests. While in the previous section we assessed the impacts of changing non-forest land into plantation forests, the expansion of intensively managed tree plantations might be also taking place at the expenses of forests with higher environmental value, such as semi-natural forests or even primary and old-growth forests (see definitions in Table S1). This conversion can take place directly, as it is plausibly taking place in the US South as a result of increased bioenergy demand [12,69], or as an indirect effect of afforestation interventions, for instance, when unprofitable agricultural land is abandoned and afforested with tree plantations leading to the deforestation of other areas of native forest to create new agricultural land [68,70].

Fig. 6 illustrates the supply chain for bioenergy production from conversion to plantation, as well as its counterfactual, in which we assume that the existing management, or lack thereof, of the naturally regenerating forest remains unchanged. The magnifying panel illustrates the five main factors whose combination produces the four pathway archetypes defined for this intervention (Table S3).

The potential impacts of this intervention on local biodiversity and ecosystems are numerous and negative.[4] For instance, MacKay et al. [71] and Demarais et al. [72] stress how the ecological value of tree plantations compared to natural forests is often low due to several factors, such as paucity of habitat components associated with tree senescence (deadwood and mature trees), limited structural complexity both in canopy (even-aged, monoculture) and in understory vegetation (sparse, often actively removed), limited capacity of habitat for biodiversity, lower carbon storage capacity, and lower levels of soil organic matter. The impact categories selected for this intervention are in Table S4.

2.2. Qualitative impact assessment method

2.2.1. Qualitative impact assessment on ecosystem condition and biodiversity

Life Cycle Assessment is a tested and proven methodology to account for environmental impacts associated to products and supply chains. However, despite recent advancements, the review by Crenna et al. [41] highlights a lack of fully mature methodologies that are apt at capturing the impacts of products on all attributes of biodiversity or ecosystem condition in an appropriate and complete manner. Therefore, we rely on a literature review (see SM for review protocol) and a qualitative assessment to synthesize the impacts of the interventions selected on local forest biodiversity and ecosystem condition.

For each paper reviewed we assessed the impact of each pathway across the selected impact categories. We then assigned each pathway to one of the following four broad-ranging qualifiers:

1. **High risk**: negative effects on biodiversity attributes or ecosystem condition are very likely or certain;
2. **Medium/high risk**: the pathway is likely to have negative impacts on biodiversity or ecosystem condition, but the final impact could be small or large in magnitude depending on other confounding variables (e.g. landscape availability of deadwood, local conditions, conservation strategies, local forest management, etc.);
3. **Medium/low-risk**: the pathway is likely to cause little or negligible negative impacts on local biodiversity or ecosystem condition, but specific conditions should be investigated to make sure that is the case;
4. **Neutral – Positive**: The pathway is very likely or certain to cause either negligible or positive effects on biodiversity attributes or ecosystem condition.

To be noticed that these qualifiers represent the potential risk associated with the pathways, while the actual risk should be evaluated based on existing local conditions and regulations, as well as on the actual implementation and enforcement of such regulatory or voluntary principles [73–75].

[3] It is important to clarify the distinction between afforestation and reforestation within FAO definitions [170], which we use, and the concepts as defined in the broader literature on restoration ecology. In the latter, it is often understood that afforestation represents the planting of trees where they did not historically occur (even though climatic conditions might support forest ecosystems), while the term reforestation represents the planting of trees (or other activities favouring natural regeneration) in areas that were deforested in modern times. By following FAO's definitions we categorise afforestation as the deliberate planting or seeding of trees on non-forested land, irrespectively of historic land use, while reforestation refers only to the re-establishment of trees on a piece of land still classified as forest (e.g. on temporarily unstocked areas).

[4] Pawson et al. [130], pag. 1205: "In a world where there are large areas of degraded (formerly forested) land suitable for reforestation, those plantations that replace natural forests rightly deserve criticism".

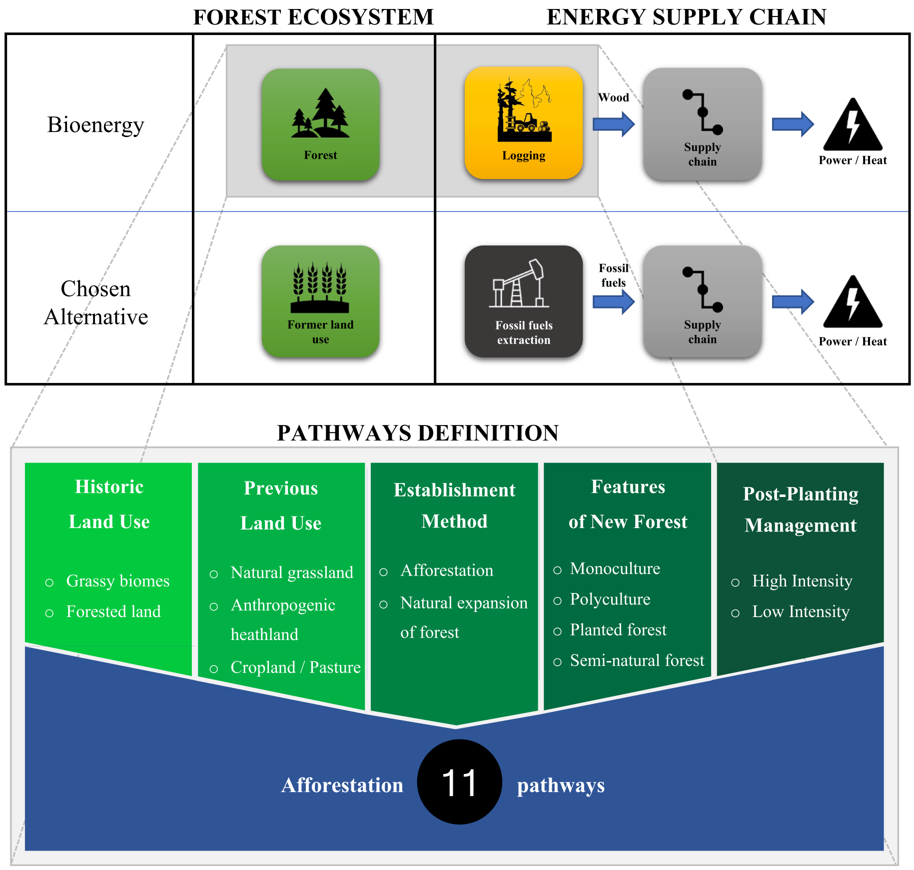

Fig. 5. Supply chain and counterfactual for the production of energy from intervention 'Afforestation'. The magnifying panel illustrates the main factors through which 11 archetypical pathways are defined.

2.2.2. *Qualitative impact assessment on carbon emissions*

As noted above, carbon accounting exercises for forest bioenergy are abundant in the literature, applying different methodologies, perspectives, and spanning many different scenarios and supply chains. It is out of the scope of this paper to evaluate all the facets of the issue in depth. Our departing point is the review study by Agostini et al. [16] who produced a qualitative assessment of the carbon impacts of various forest bioenergy pathways.

One important lesson learned is that the carbon impacts of forest bioenergy pathways are time-dependent and that a useful metric to compare the GHG emissions of a multitude of bioenergy pathways is the so-called 'payback time'. In this study the term 'carbon debt' indicates the phenomenon by which a bioenergy pathway initially produces higher carbon emissions compared to a fossil counterfactual system, and the term 'payback time' is the time needed for the carbon debt to be repaid by continuously replacing the chosen fossil-based system and for the bioenergy system to begin providing carbon mitigation. A schematic representation of this concept is depicted in Fig. 7. The curves in green represent the cumulative biogenic-CO_2 emissions obtained by comparing the use of wood for energy versus an alternative in which energy is provided by fossil fuels. For instance, considering the removal of logging residues, the green curves would represent the loss of carbon in the C-pool of deadwood when this is combusted for energy instead of being left to decay on the forest floor. The multiple green lines represent different bioenergy characteristics, for instance they could represent the use of logging residues with different decay rates. The blue lines represent the cumulative emissions of fossil-CO_2 generated by the use of arbitrary fossil fuels with different carbon intensities for energy production in the chosen alternative. The payback time is found at the interception between the blue and the green lines.

As opposed to impacts on biodiversity, payback times can be calculated with great precision and accuracy, however, the final results are determined by the specific assumptions of the fossil system replaced. Not only which fossil fuel is replaced constitutes a value choice, but the fact itself that a fossil fuel might be the only alternative energy source constitutes a value choice that determines the result. In fact, if a source of energy other than fossil fuel is chosen for comparison (e.g. photovoltaics or wind) there would not be any payback time at all. Identifying what energy source and technology is likely to be replaced by forest bioenergy, and in which amount, is extremely complex; given that there are mandatory targets for renewable energy sources in Europe, the alternative to bioenergy would more likely be other renewable energy sources than fossil fuels. Nonetheless, payback times may still be useful to evaluate time-related climate impacts of forest bioenergy, as far as the conceptual limitation of the approach are understood and properly communicated (i.e. they are what-if scenarios based on value choices). Agostini et al. [23] present a detailed discussion on this topic.

Since, we are interested in generalized time-related results for each of the pathways defined, this is only possible by defining very broad-ranging intervals of payback times. Thus, the four qualifiers defined for the carbon accounting assessment are the following:

4. **Short-term**: these are pathways which are likely to achieve carbon emissions savings compared to fossil sources immediately or within one or two decades.
5. **Likely medium-term**: these are pathways which are likely to achieve carbon emissions savings within three to five decades.
6. **Unlikely medium-term**: these are pathways which are not likely to achieve carbon emissions savings before five decades.

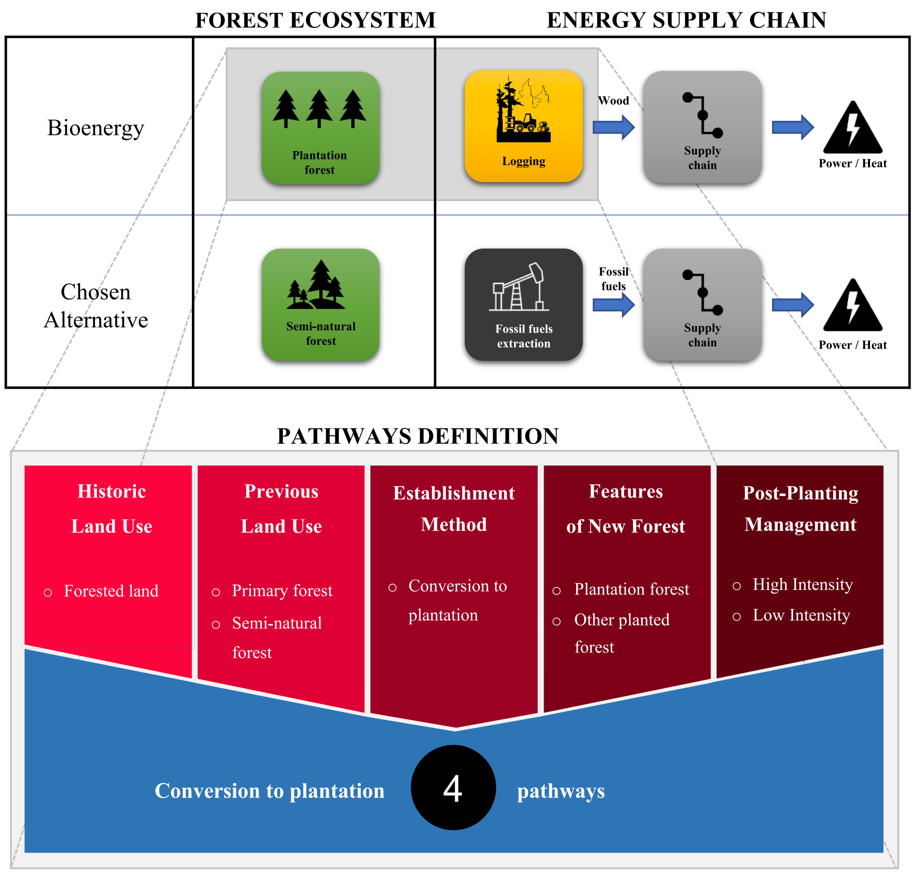

Fig. 6. Supply chain and counterfactual for the production of energy from intervention 'Conversion to plantation'. The magnifying panel illustrates the main characteristics through which 4 archetypical pathways are defined.

7. **Long-term**: these are pathways which are likely to achieve carbon emissions savings only in a century scale or even never.

2.2.3. Synthesis and nexus matrix

Our final goal is to allocate each pathway assessed in one of the four quadrants in Fig. 8. Pathways in the first and fourth quadrants are relatively clear situations in which no dominant trade-offs are evident. These could therefore clearly be targeted for governance measures: win-win pathways in quadrant 1 should be incentivised, while lose-lose pathways in quadrant 4 should be discouraged. Conversely, trade-offs between climate mitigation and biodiversity can be identified or presumed for pathways in quadrants 2 and 3. Pathways in quadrant 2 may be likely to mitigate climate change, but they are also likely to negatively impact local biodiversity. These are what Lindenmayer et al. (2012) termed as "bio-perversities"[5] [76]. Pathways in the third quadrant, instead, are likely to improve local ecosystem condition, but might not mitigate climate change in the short term or at all. In these cases, bioenergy production might be seen as a by-product of operations carried out for biodiversity conservation or ecosystems' restoration.

2.3. Delimitations of the assessment

Conscious that every assessment result is conditional on the assumptions adopted [77,78], we gather here the main and most influential assumptions driving our assessment and the inevitable limitations:

1. The precautionary principle is the overarching worldview which has driven the goal and scope of the assessment. We subscribe to a strong

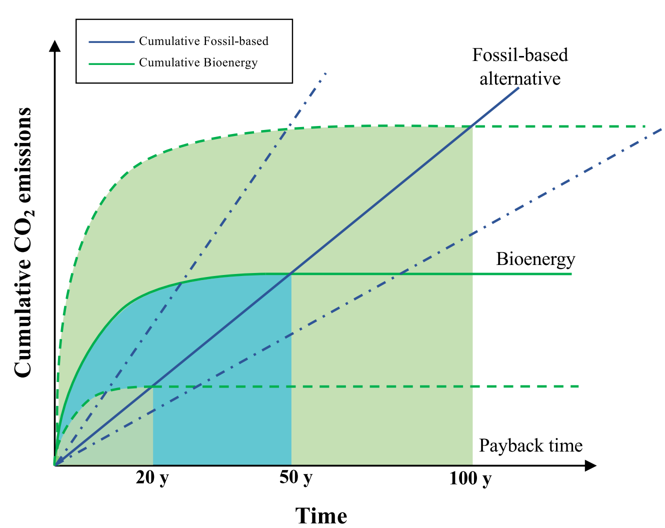

Fig. 7. *Visual description of payback time and the four bins for the qualitative assessment. Green Lines: change in the forest carbon stock due to bioenergy production; Blue lines: accumulated reduction in carbon emissions from substitution of fossil fuels. Dashed lines represent arbitrary alternative curves. Adapted from Agostini* et al. *(2014)* [16].

[5] Lindenmayer et al. [76] defined bio-perversity as "the negative biodiversity and environmental outcomes arising from a narrow policy and management focus on single environmental problems without consideration of the broader ecological context".

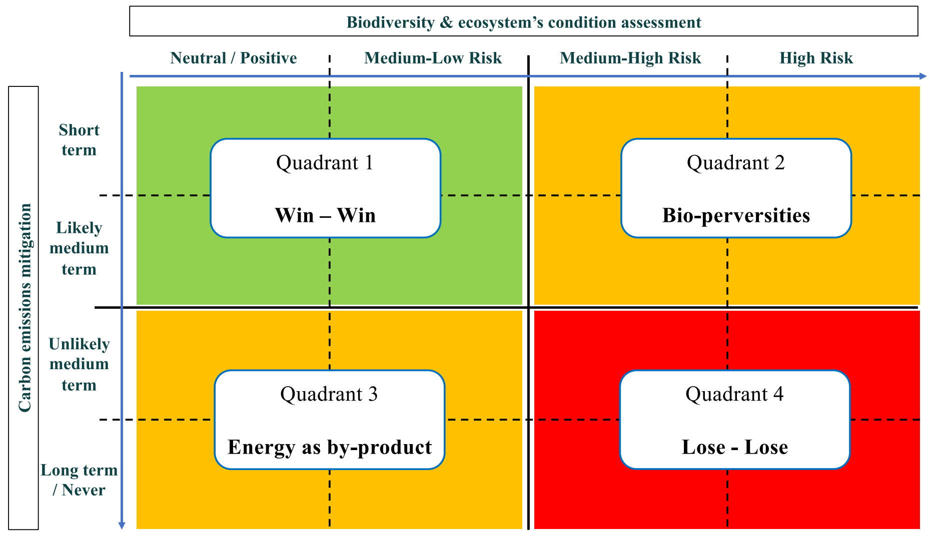

Fig. 8. Nexus matrix and the meaning of each quadrant.

sustainability worldview [79], especially that alternatives exist to bioenergy as a mitigation strategy, while healthy, functional ecosystems and the services they provide, and the existence value of the tapestry of life on Earth cannot be replaced by anything created by human ingenuity.

2. Of all the facets of forest bioenergy sustainability, we focus here only on the two issues of climate change and ecosystems' condition. We thus explicitly exclude many other aspects that characterize the broader bioenergy sustainability assessment, such as the role of bioenergy on electricity grid stabilization, on energy security, and on socioeconomic dimensions such as rural development, income, and employment. We also ignore other environmental impacts, such as air pollution [80,81], and other non-GHG climate forcers, such as Near Term Climate Forcers (aerosols, ozone precursors) and biogeophysical forcers (e.g. surface albedo change).
3. The impacts of each bioenergy pathway are evaluated against a chosen fossil alternative. The results of the assessment, thus, should be interpreted as conditional to the reference chosen.
4. Our analysis focuses on a selected sub-set of interventions and pathways and we thus do not claim to capture the whole range of possible risks and benefits associated with forest management interventions linked to bioenergy.
5. Our assessment on carbon and biodiversity impacts is based on direct impacts only and excludes indirect, market-mediated, second-order effects. These might mitigate or worsen the direct impacts assessed here, but their assessment would require a broader modelling framework. Especially, effects of the scale of demand of wood for bioenergy and other uses, such as for instance, rebound effects in the energy market [82], indirect effects on wood products markets, and potential indirect land use change effects linked to afforestation of cropland, are not assessed in our research. Additionally, we do not consider BioEnergy with Carbon Capture and Sequestration (BECCS) technologies.
6. Since our main goal is to generate a high-level synthesis of knowledge and distil lessons learnt, our literature review focuses mainly on already existing reviews and meta-analysis, and only on English language literature. Thus, the literature reviewed might not capture the totality of the available information. For instance, we notice a research bias for the impact of logging residues removals so that most of the studies refer to temperate or boreal forest ecosystems. Furthermore, there appears to be a paucity of on-site empirical studies comparing the status of plantations with natural, native forests in the US South [83], even though those play a significant role in the supply of wood pellets to the EU.
7. The qualitative assessment in this study is based on the literature reviewed, but it still inevitably reflects our own expert judgement and the assumptions illustrated above; different authors could come to slightly different conclusions reviewing the same exact literature. However, we believe the synthesis of knowledge in this paper is a good starting point to facilitate the comparison among pathways, highlighting risks and red flags and contributing to an incremental understanding of the impacts of bioenergy on carbon emissions and ecosystems' condition.

3. Review and synthesis of impacts

This section presents the results of the literature review for each separate intervention and the resulting qualitative assessment of the impact of each pathway on biodiversity attributes. Finally, the last subsection also presents the carbon impact assessment for each intervention.

3.1. Removal of logging residues

Table S5 provides a synthesis of the results found in the 19 studies and 34 case studies reviewed, including comments for each study, describing the taxonomical groups considered, spatial and temporal scales, type of deadwood, as well as other abiotic and biotic factors. Fig. 9 represents all the archetypes defined for this intervention and their qualifiers.

From the literature, a general consensus emerges that CWD (e.g. snags, logs, high stumps) are ecologically more important than FWD as a habitat for saproxylic species (e.g. Refs. [84–87]), and that removal of CWD has a negative impact both on species richness and abundance of saproxylic species (e.g. Refs. [88–90]). Pathway nr. 1, thus, clearly places high risk on forest ecosystems. PEFC certification standards explicitly recommend that standing and fallen deadwood shall be left in quantities and distribution necessary to safeguard biological diversity. However, several studies [91–93] have found that the translation of this principle into practical guidelines has been insufficient, in quantity and quality, compared to what would be needed to maintain healthy ecosystems.

Existing literature and harvesting guidelines [75] often identify and recommend retention (or removal) thresholds for various types of

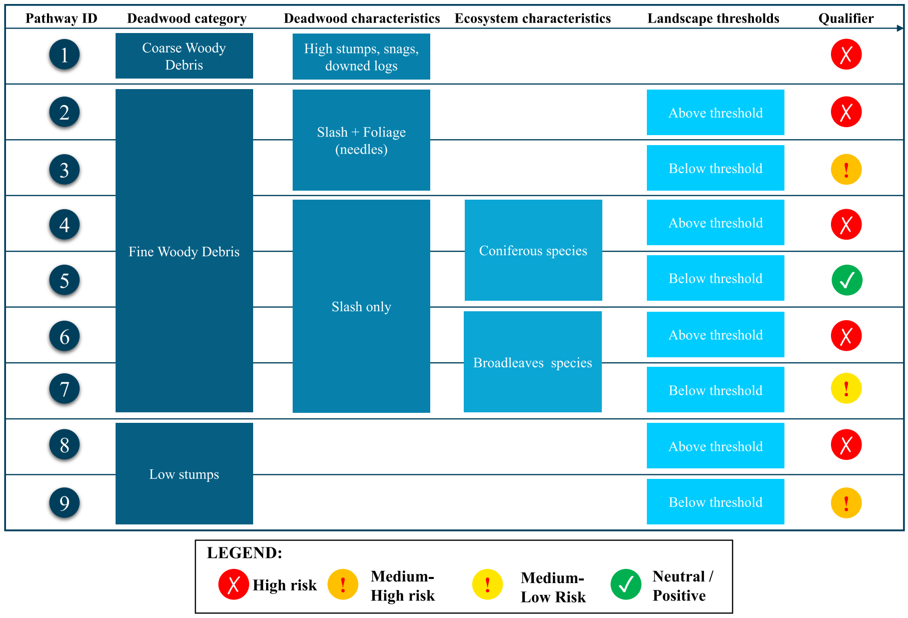

Fig. 9. Archetypical pathways representing a synthesis of evidence from literature review for the 'Removal of logging residues' intervention. The risk qualifiers refer to potential risk, thus unmitigated by existing legislation, recommendations, or voluntary certification schemes.

deadwood aimed at minimizing impacts on biodiversity and soils. Thus, pathways 2 to 9 differentiate risk qualifiers based on the amount of residues considered to be removed. All pathways that consider the removal of a large share of the available residues (pathways nr. 2-4-6-8) are qualified as 'high risk'. There is consensus in the literature about the importance of implementing retention thresholds not only for CWD, but also for FWD and low stumps (e.g. Refs. [94–96]). Titus et al. [75] report scattered data concerning existing guidelines for retention of various deadwood components; for instance, they find that half of the ten countries in Europe included in their study tackled post-harvest retention for FWD, 70% had guidelines for stump removal, while only 30% of the countries had guidelines on CWD retention. Additionally, voluntary certification standards do not explicitly mention slash or low stumps retention [73,74]. Based on ecological modelling and conditions in Sweden, for instance, de Jong et al. [95] suggest that harvesting 50% of slash and 10–20% of stumps in spruce-dominated landscapes might have limited to negligible impact on biodiversity in general and a marked effect on only a few species. In practice, Thiffault et al. [97] reviewed the removal rates of harvest residues (mainly slash, stumps excluded) in boreal and temperate forest trials and found an average rate of 50% being removed, with an average in Finland and Sweden of 76%. Evaluating the appropriate thresholds will have to be done locally, also depending on the exact goal of the conservation intervention. De Jong & Dahlberg [87], for instance, focused on the potential impacts of residues removals on Species of Conservation Interest (SCI) and red-listed species, while Ulyshen [59] highlighted the importance of certain taxa in promoting wood decomposition processes, such as wood-boring beetles and termites, and that impacts on these functional groups might be ecologically more consequential than general species richness metrics. However, other authors disagree with focusing on specific taxa or functional groups, claiming that time-lag effects and the so-called 'extinction debt' would suggest a more precautionary approach for which any species decline is considered as dangerous and significant (e.g. Ref. [98]). Snäll et al. [96] present another counter-argument to focusing solely on red-listed species, stating that a key criterion for inclusion into the IUCN Red-list of threatened species is evidence of a population decline above 50% in 10 years, however this means that species that are not yet red-listed may become so as an effect of the intervention.

De Jong et al. [87] report that the ecological importance of FWD of deciduous species is higher compared to deadwood of coniferous species. Therefore, while pathway 5 is assigned a low-risk qualifier, pathway 7 is qualified with a medium-low risk.

Pathways 2 and 3 reflect the potential negative impacts of removing foliage and needle, in addition to slash, on nutrients availability and tree growth, as found by Achat et al. [99,100]. Nilsson et al. [101] found that a similar fraction of needles is removed whether the residues are left stacked on clear cut site for a whole summer or they are transported directly to the roadside; they thus concluded that the retention threshold plays a bigger role in maintaining nutrients than de-needling operations, which is why pathway 2 is assigned a high-risk qualifier. On the other hand, pathway 3 is assigned a medium-low risk because the need for nutrients' compensation (e.g. through ash recycling) should be evaluated on a site-specific basis, depending on local site conditions and residue removal levels. Additionally, harvesting guidelines already often advise on leaving residues on site for a certain period before collection in order to dry and shed needles and leaves [75].

Pathways 8 and 9 reflect the importance of local specificities in the assessment of the impacts of low stumps removal. Most studies agree on the need for a removal threshold leading to the high-risk qualifier for pathway 8. However, while low stumps are often identified as important habitats [94,102,103], there does not seem to be a consensus on the actual ecological impact of low stumps removal [104], which leads us to assign a medium-high risk for pathway 9, meaning this should be carefully examined on a case-by-case basis. Locally defined guidelines and recommendations often exist to regulate the removal of stumps [75,104].

Finally, even though not specifically captured in our archetypes, as indicated in Figure S2, mechanical operations during the collection of logging residues might have negative impacts on habitats and existing retention structures (e.g. high-stumps and downed dead logs) even when they are not removed. Additionally, the temporary roads used for forest management may cause both soil compaction and soil losses due to run-off with heavy rain and significant slopes [105,106]. SFM certification standards tackle this potential damage: for instance, PEFC standards state that 'tending and harvesting operations shall be conducted in a way that does not cause lasting damage to ecosystems. Wherever possible, practical measures shall be taken to maintain or improve biological diversity' [74].

Finally, as a sub-category of this intervention we have included a recent meta-analysis by Thorn et al. [107] investigating the impact of salvage logging on several taxa. They found significant negative effects on saproxylic species especially in salvage operations after fires and windthrow disturbances. They state that these disturbances create specific habitats and structures for many species which are removed by salvage operations. On the other hand, they found positive impacts of salvage operations after pest outbreaks. These findings are in line with other calls from the scientific community to limit post-disturbance management [108]. Despite these findings, we decided not to define archetypes for salvage logging operations because the overall impact on climate and biodiversity would be strongly influenced by assumptions on counterfactual (i.e. what would happen if salvage operations did not take place?) and we invite further research on this topic in our recommendations.

3.2. *Afforestation*

Table S6 shows the assessment of the 35 reviewed case studies, and Fig. 10 illustrates the chosen archetypes and the qualifier assigned to each of them. As highlighted in section 2.1.3, we assessed the impacts of all the afforestation pathways, albeit bioenergy demand, on its own, is likely to lead mainly to the creation of intensively cultivated monocultures.

Firstly, there is consensus in the literature that afforestation of primary, ancient grassland ecosystems that were never forests, may have detrimental effects on local biodiversity; some authors compare these effects to the destructive effects of deforestation [109–114]. This is largely valid also for semi-natural grasslands and anthropogenic heathlands. In these ecosystems, closed-canopy forest did not historically develop because of natural processes such as fire or megafauna grazing, or because of extensive management by local people. Biodiversity adapted to open land has thus evolved in those ecosystems over thousands of years, and afforestation or tree planting of closed-canopy forests is considered as a significant threat for local biodiversity [115–117]. Pathways 10 to 12, thus, reflect the negative impacts of transforming ancient grassy biomes to closed-canopy forests. Similarly, pathways 13 to 16 reflect the high risk of loss of species adapted to open ecosystems when tree planting takes place in anthropogenic heathlands, or even when land abandonment would eventually result in natural forest regeneration. All these pathways would be discouraged or altogether forbidden by PEFC certification standards and would also go against the Pan-European guidelines for reforestation and afforestation (Guideline nr. 18) [118]. Nonetheless, the voluntary nature of these guidelines and the potentially limited application of them outside the EU warrant the high-risk qualifier for these pathways.

Pathways 17 to 20 capture the impacts of afforestation interventions in ecosystems deforested in modern times for agricultural purposes. Multiple archetypes are defined based on different establishment methods, plantation features, and post-planting management, to capture the differential impacts associated to various management objectives for the newly established forest. In fact, Cunningham et al. [119] considered four broad categories of environmental benefits that afforestation could provide compared to agricultural land use: carbon sequestration, biodiversity conservation, water yield, and water quality. They concluded that no single type of afforestation strategy will simultaneously maximize all the environmental benefits. Having this in mind then, pathways 19 and 20 capture situations in which the main goal of afforestation is not only production of wood, but rather a mix of production and biodiversity conservation. These pathways for forest expansion may take place through active tree planting or by creating the conditions for natural forest succession, and through different planting strategies and post-planting management. Several studies provide some practical recommendations to enhance biodiversity in planted forests, as collected in Fig. 11. We coin these management strategies as ‘Low intensity management’ (similarly to Duncker et al. [120] definition of ‘Close-to-Nature forestry’), and allow pathways 19–20 to be qualified as Neutral/positive. These pathways are also likely to generate ecosystems with improved resilience to natural disturbances and thus lower vulnerability to future climate change [121,122].

Pathways 17 and 18 reflect conditions in which plantations are established with the main goal of maximizing productivity of wood, and thus are intensively managed. These pathways might be closely linked to bioenergy demand because, if afforestation efforts are left mainly to economic forces, the push for short-term economic gains might promote the establishment of intensively-managed monocultures based on fast-growing exotic species [123]. These pathways would fall in the categories defined by Duncker et al. [120] as ‘Intensive Even-aged forestry’ and ‘short rotation forestry’, including operations such as: short

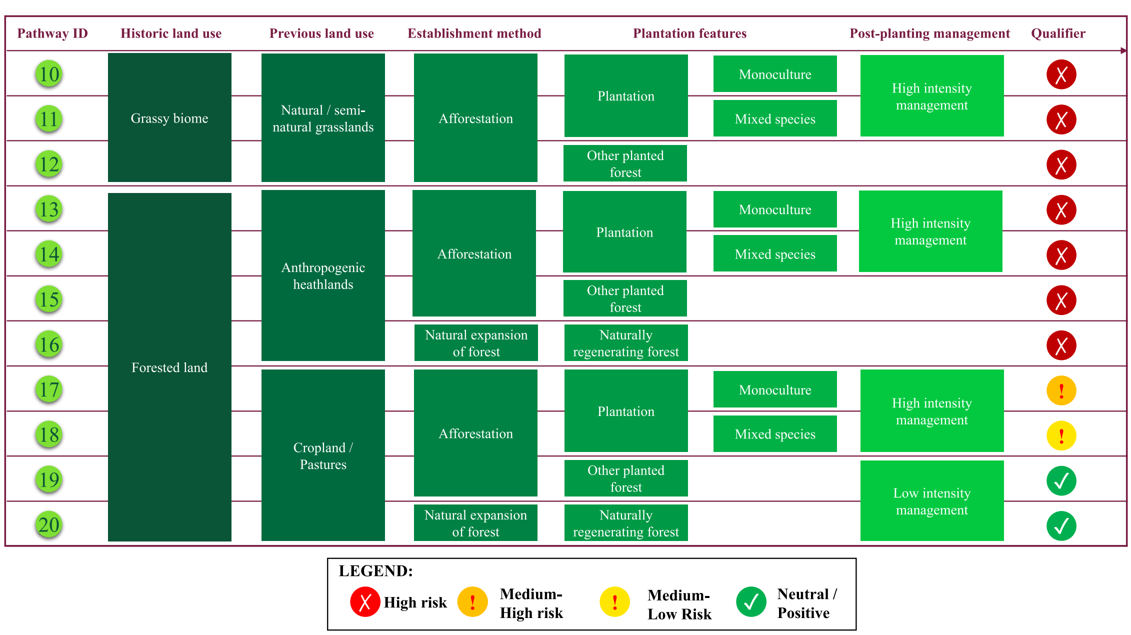

Fig. 10. Archetypical pathways representing a synthesis of evidence from literature review for the ‘Afforestation’ intervention. The risk qualifiers refer to potential risk, that is, unmitigated by existing legislation, recommendations, or voluntary certification schemes.

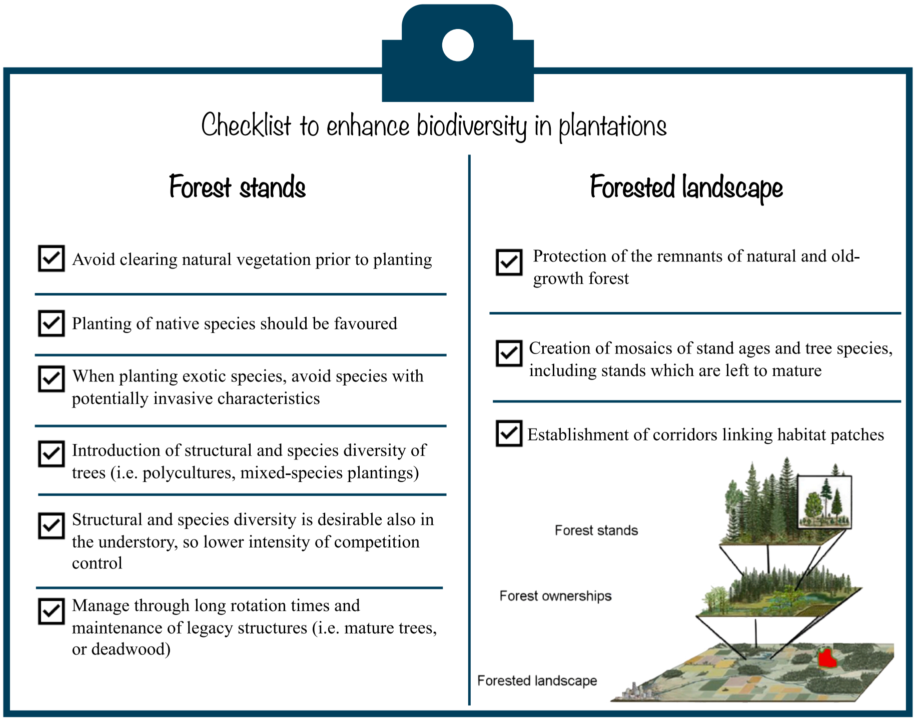

Fig. 11. *Practical recommendations to enhance biodiversity in plantation forests. Checklist elaborated from:* [71,130,131,136–138]. *Figure modified from* Ref. [138].

rotations, fertilization, site preparation, removal of deadwood, use of fast-growing species, etc. We differentiate these pathways based on the planting of a single or multiple species. Indeed, the literature reviewed has revealed that afforestation by monocultures may have some negative outcomes on local biodiversity and local water cycle (e.g. Refs. [124–128]). Nonetheless, monoculture plantations can have an important role within the landscape mosaic and even a patchwork of monoculture stands with different species could create a varied enough structure to maintain or improve local biodiversity compared to degraded agricultural land [124]. As a result, pathway 17 is classified with a medium-high risk level. On the other hand, plantations employing a mixture of tree species might not only be beneficial for local biodiversity but might also be equally, or more, productive than monocultures [129]. This is an ongoing field of investigation, and research is focusing on designing effective species mixtures with high complementarity, so as to guarantee high productivity while at the same time increasing resilience to pests and adaptive capacity to climate change [130–132], as well as improved structural and functional diversity [133–135]. Hence, pathway 18 is classified with a medium-low risk level, because optimisation of planting design will need to be achieved on a case-by-case basis.

3.3. Conversion to plantation forests

Table S7 presents the results of the assessment for the 28 case studies collected from the literature, and Fig. 12 illustrates the qualitative assessment for all the pathways defined.

The assessment in Fig. 12 shows high or medium-high risks for all pathways considered. This reflects the general consensus across the literature that substituting semi-natural forests, often composed by naturally regenerating native species, with intensively managed plantation forests has negative consequences for local biodiversity across the regions and taxa studied [130–132,139].

Firstly, Pathway 21 captures the clear consensus about the negative impact of substituting primary and old-growth forests with very limited or absent human influence, with plantation forests (see e.g. Refs. [53, 140]). Numerous species, in fact, are strictly limited to primary and old growth forests and are lost when these are transformed into plantations [141]. This pathway might appear implausible also in light of the recent calls for strict protection of the remaining primary and old growth

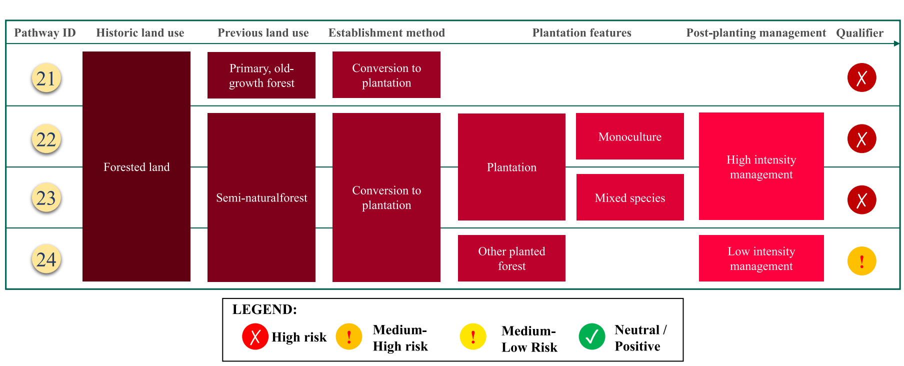

Fig. 12. Archetypical pathways representing a synthesis of evidence from the literature review for the ‘Conversion to plantation forests’ intervention. The risk qualifiers refer to potential risk, that is, unmitigated by existing legislation, recommendations, or voluntary certification schemes.

forests in Europe [31]; however, gaps in mapping the exact extent and location of these forests [142,143] and existing conflicts on management strategies [144,145], show that the risks of exploitation and conversion of these ecosystems are unfortunately still relevant even within Europe, and certainly even more so outside of Europe (e.g. Ref. [146]).

Pathways 22 to 24 reflect the conclusion reached by several studies that replacing semi-natural forests with plantations has a negative impact on various attributes of biodiversity (see e.g. Refs. [124,125,136,137,147,148]). Even though Castaño-Villa et al. [136] found that mixed species plantations showed fewer negative impacts compared to monocultures, because more structural complexity favours bird biodiversity, both pathways are assigned a 'High-risk' qualifier. Indeed, MacKay et al. [71] showed that even mature plantations (specifically, 40–50 years old spruce plantations in Canada) are not able to provide suitable habitat for bird species adapted to mature or to old-growth forests, and Haskell et al. [149] found that pine plantations in US South resulted to be impoverished in diversity of bird species even as compared to exurban areas with human occupation. Furthermore, the simplified structures of plantations might make them less resilient to natural disturbances and more susceptible to climate change compared to natural forests [121]. Even though Paquette & Messier [131] make the case that market-mediated effects could also lead to positive outcomes, such as an increase in high-productivity plantations might create the conditions to decrease intensity in other forested areas and expand forest areas with full protection, we reiterate that the results in Fig. 11 only refer to direct impacts.

Finally, pathway 24 captures situations in which semi-natural forests are converted to planted forests with low management intensity. Castaño-Villa et al. [136] found this conversion to have a neutral impact on the species richness of birds and even a positive effect on species abundance. Nonetheless, we qualify it with a Medium-High risk level because, before any such conversion is endorsed, many local conditions should be evaluated to avoid negative impacts. Nonetheless, this pathway may be relevant because the share of planted and plantation forests is increasing at the expenses of semi-natural forests and they will thus have to carry an increasingly larger role in maintaining suitable habitats for forest biodiversity.

3.4. Carbon impacts of the interventions: synthesis

As stated above, the main added value of this work is to expand the knowledge about forest bioenergy impacts on local biodiversity and ecosystems. Therefore, our evaluation of potential carbon impacts of the pathways analysed rely largely on our past reviews on the topic [12,16,37]. Table 1 summarizes our assessment of the carbon payback times for all the pathways analysed.

4. Discussion

4.1. Climate and biodiversity nexus

As shown in the matrix in Fig. 13, our results indicate that it is possible to identify a limited number of win-win pathways that can both mitigate carbon emissions in the short term while not deteriorating, or even improving, the condition of forest ecosystems. Specifically, we find that collecting slash within the limits of locally recommended thresholds could generate energy without deteriorating forest ecosystems and at the same time potentially contribute to reducing GHG emissions. Similarly, afforesting former agricultural land with mixed species plantations or with naturally regenerating forests would contribute to climate change mitigation by enhancing the terrestrial sink even before producing biomass for energy, while at the same time improving the condition of ecosystems.

In contrast with the win-win pathways, eight out of our 24 pathways are categorized in the lose-lose quadrant and should be discouraged. For instance, the removal of CWD and low stumps can be detrimental to forest ecosystems while not contributing to reducing carbon emissions in the short, or even medium term, compared to fossil sources. Further, as expected, the conversion of primary and old growth forests to plantations aiming to provide wood for bioenergy would be extremely negative for local biodiversity and ecosystems. In addition, it would provide no carbon mitigation benefits in the short-medium term. Similar considerations hold for the conversion of semi-natural, naturally regenerating forests to high-intensity management plantations.

Pathways in quadrant 2 constitute bio-perversities, which might lead

Table 1
Evaluation of payback times for the pathways analysed.

Intervention	Main mechanism	Qualitative assessment of payback time ranges
Removal of logging residues	Payback time depend strongly on the decay rates considered [16,57]	• FWD (Pathways nr. 2 to 7): 'Short-term' qualifier due to generally fast decay rates. • CWD (Pathway nr. 1): 'Long-term' qualifier due to low decay rates and subsequent very long payback times. • Low stumps (Pathways nr. 8–9): 'Unlikely medium term' qualifier, considering a decay rate between 3%/year and 6%/year [57,150]. A range of uncertainty is considered due to broad range of decay rates reported in literature (0.7%/year – 11%/year [104]).
Afforestation	The overall carbon balance of afforestation pathways derives from the net result of two main components: 1) accumulation dynamics of terrestrial C-stock and overall difference in C-stock between afforested land and the alternative at steady state; 2) substitution effects of the bioenergy produced.	• Afforestation of agricultural land with plantations (Pathways nr. 17–18): 'Short-term' qualifier due to accumulation of terrestrial C-stock [16,50,151]. • Afforestation of grasslands (Pathways nr. 10 to 15): 'Likely medium-term' qualifier is assigned because, even though SOC stocks would be similar in plantations and natural grasslands, plantations would sequester additional C-stock in aboveground biomass and produce wood for substitution of fossil sources [16,50,151].
	While the substitution would start to generate benefits only after the first harvest, the terrestrial carbon sink might generate C-benefits already in the short-term depending on the land use transition considered.	• Afforestation with naturally regenerating forests managed with lower intensity (Pathways nr. 16–20): 'Unlikely medium-term' qualifier because growth rates are assumed to be slower compared to plantations. A range of uncertainty is considered due to the lack of studies and the likely variation in productivity.
Conversion to plantation forests	This intervention leads to a large release of carbon at the time of conversion, a likely lower stock of carbon at the maturity of the stand, and potentially lower C-stock in the soil [17]. However, the productivity of wood is usually higher in plantations compared to semi-natural forests due to faster growth rates and intensive management.	• Conversion of semi-natural forests (Pathways nr. 22 to 24): 'Unlikely medium term' qualifier is assigned and a range of uncertainty considered, since payback times for this intervention were calculated to be between 60 and 120 years for US South [152,153]. • Conversion of primary forests (Pathway nr. 21): 'Long-term' qualifier is assigned based on Mitchell et al. [154].

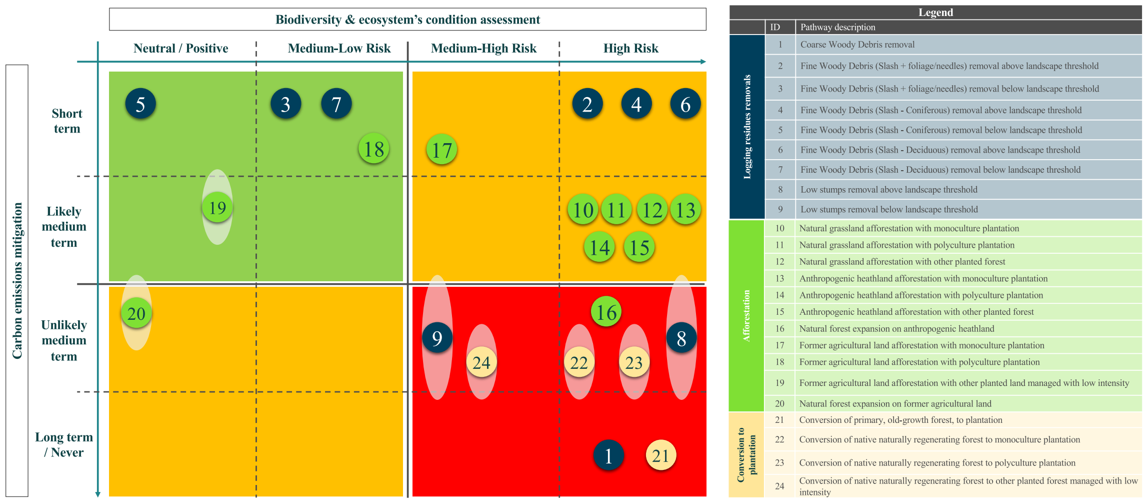

Fig. 13. Qualitative assessment of the archetypical pathways indicating climate and biodiversity impacts. Dark blue symbols represent pathways referring to 'logging residues removal' intervention, green symbols refer to pathways for 'afforestation', and gold symbols refer to 'conversion to plantation' interventions. Uncertainty ranges are placed where payback time for carbon emissions could not be placed within a single one of the defined levels. The position of the interventions within each quadrant is arbitrary.

to climate change mitigation but at the expense of local ecosystems. For instance, in this quadrant we can find afforestation of former agricultural land with monoculture plantations: this intervention is likely to lead to carbon benefits in the short-term, but the impacts on local ecosystems should be evaluated carefully, for instance in the framework of landscape management and climate change resilience [130,155]. Afforestation of natural grasslands or anthropogenic heathlands is expected to produce carbon benefits in the medium term at the cost of deteriorating ecosystems condition and local biodiversity, especially species adapted to open land habitats.

4.2. Policy implications

Our findings lead to clear implications for the governance of bioenergy sustainability, as listed in Table 2. These measures tackle each intervention and pathway assessed in this study and can be considered as a checklist for decisionmakers at international, national or subnational levels to test whether forest management guidelines and bioenergy strategies in place are fit for the purpose of promoting win-win solutions and avoiding lose-lose and bio-perverse options. As an example, we compare the policy implications of our findings to the relevant measures included in the 'Fit for 55' package recently adopted by the European Commission [36]. We believe this exercise will support the future legislative steps that will lead to the promulgation of these legislations.

The EU Renewable Energy Directive (henceforth REDII) [49] is certainly the main legislative document, amended within the package in July 2021, that governs the sustainability of forest bioenergy in the EU. The REDII, adopted in 2018, introduced in Article 29(6) mandatory risk-based sustainability criteria for forest biomass, with the aim to ensure compliance with sustainable forest management laws and principles (see detailed description of the criteria in Section 10 of SM). We assess that the proposed amendments [156] to these criteria are aligned with our findings: by explicitly excluding the use of low stumps and roots and by requiring that locally appropriate thresholds for deadwood removal are ensured, the lose-lose pathways 2-4-6-8-9 are in principle excluded. We argue that our findings would warrant a complete exclusion of any CWD removal for energy and we recommend the locally appropriate threshold for CWD removal for energy to be equal to zero (eventually accounting for specific exceptions).

Further, our review highlights the negative impacts of clearing semi-natural, primary and old-growth forests to establish intensively managed plantations and other planted forests. The proposed amended REDII expands specific no-go areas to forest biomass (Article 29(3)), meaning that biomass for bioenergy cannot be directly produced from land that was, at any time after 2008, classified as highly biodiverse grassland, primary forest, highly biodiverse forest, or a protected area. This amendment introduces additional safeguards ensuring that forest biomass for energy is not associated to the afforestation pathways with the most negative impacts, i.e. those taking place on natural or also anthropogenic high natural value grasslands or heathlands. In addition, it would also forbid sourcing any wood for energy production from plantations established on converted highly biodiverse forest, primary, and old-growth forests. For instance, native ecosystems in the US Southeast are rich in endemic species and several important biodiversity hotspots have been recognized in the region [157,158], thus if semi-natural forests in the region were classified as highly biodiverse forests, any pine plantation established after 2008 would be excluded from exporting wood pellets to the EU. However, according to the text in the review of the Directive, plantations established on semi-natural forests not classified as highly biodiverse will be potentially eligible to supply wood for bioenergy. According to our findings, these interventions (see pathways 22-23-24) would not deliver climate nor biodiversity benefits, thus lose-lose solutions would still be considered as 'sustainable bioenergy' supply. Another crucial aspect is that an operational definition for 'highly biodiverse forests' is currently lacking and should be urgently agreed upon.

Several of the afforestation pathways assessed in this paper are not primarily driven by bioenergy demand, and they are better managed through other measures, such as within the EU Forest Strategy [159]. The Forest Strategy translates the pledge to plant 3 billion trees by 2030 introduced in the EU Biodiversity Strategy [31] into concrete actions. Specifically, the pledge stresses that the main guiding principle of tree planting should be to "plant and grow the right tree in the right place, for the right purpose". Further, the pledge explicitly stresses that afforestation of primary, ancient grasslands, as well as semi-natural grasslands and anthropogenic heathlands should be avoided. Additionally, the pledge states that intensive monoculture plantations should not count towards the pledge and that the use of non-native species should be excluded. Despite these potential safeguards, pathway nr. 17 is not legally excluded in any of the package documents.

It should be noted that any additional demand of wood for bioenergy will simply add up to the overall demand of wood for other uses, meaning that even if wood for energy is subjected to stricter

Table 2
Governance measures resulting from this assessment. In the third column, the relevant articles within the 2021 proposal for a revised Renewable Energy Directive are mentioned. Details on these articles are presented in the SM.

Governance recommendations	Pathway affected	Comment
Forbid any use of CWD for energy purposes	1	• No explicit mention of CWD in Article 29(6) • Implicitly covered by the requirement to establish locally appropriate thresholds (Art. 29(6))
Forbid or discourage the collection and use of low-stumps for energy	8, 9	• Use of low stumps and roots for energy is excluded from receiving state aid (Art 3.3) • Use of low stumps and roots for energy should be avoided (Art. 29(6))
Define appropriate and precautionary local landscape thresholds for removal or retention of each deadwood component (FWD, CWD, low stumps)	2, 4, 6, 8	• Definition of locally appropriate thresholds for deadwood extraction is a requirement under Art. 29(6)
Forbid afforestation and tree planting on natural grasslands and heathlands	10, 11, 12, 13, 14, 15	• Wood produced from land which was highly biodiverse grassland at any time after 2008 cannot count towards the EU renewable energy target (Art. 29(3)) • EU Forest strategy explicitly recommends avoiding afforestation of these ecosystems
Discourage afforestation and tree planting of monoculture plantation forests	17	• EU Forest strategy recommends that planting of monoculture plantation forests is not counted towards the 3 billion trees target
Forbid any use of wood from plantation forests established on recently converted primary and old-growth forest	21	• Wood produced from primary and old-growth forests cannot count towards the EU renewable energy target (Art. 29(3)). • Additionally, conversion of primary forest to plantation should be avoided under Art. 29(6)). • For EU primary forests, the EU Forest Strategy also recommends strict protection.
Forbid any use of wood from plantation forests established on recently converted semi-natural forests	22, 23, 24	• No reference to conversion of semi-natural forests to plantation forests within the sustainability criteria of the REDII amendment

sustainability criteria, wood for other purposes might still be produced through detrimental practices and pathways. As highlighted by the EU Bioeconomy Strategy [160], a holistic governance is required to move towards a sustainable and circular bioeconomy. Therefore, better defining and expanding sustainable forest management to all forest products consumed in Europe, irrespective of final use and geographical origin, would be an effective measure to promote a more sustainable forest-based sector as a whole. The EU Forest Strategy with its call for new indicators and thresholds for Sustainable Forest Management certification and the forthcoming regulation on nature restoration, all certainly go in this direction.

Finally, we point out that while at EU-level the legislative framework appears to be largely in line with our findings, crucially, compliance with the EU REDII criteria for sustainable forest management rely, in a first instance, on the effective implementation of existing national or sub-national forestry legislation. Thus, a similar fitness check should be run at national scale, both for European countries as well as major trading partners. In fact, checks on existing sustainability criteria have shown that enforcement and compliance might be significant obstacles to the effectiveness of the criteria to promote sustainable forest bioenergy [161]. Similarly, while the EU is acting on its global footprint by developing measures to address the potential deforestation risks associated to imported biomass (for material or energy use alike) [162,163], attention should be placed also on imported biomass obtained from plantations established through harmful afforestation or conversion activities.

5. Conclusions and recommendations

Using literature review and knowledge synthesis we qualitatively assessed the potential impacts of 24 archetypical bioenergy pathways on forest ecosystems and biodiversity. We chose to focus on three forest management interventions which can potentially supply additional wood for bioenergy use. By combining our assessment with results from the literature on carbon payback time estimates for these pathways, we identified archetypes that may provide win-win solutions for climate and ecosystems. These mainly concern the collection and use of slash, below locally-defined removal thresholds, and the use of wood from afforestation of agricultural land with mixed-species plantations.

In contrast, one third of the pathways assessed were identified as lose-lose options. Saltelli et al. [78] suggest borrowing a 'via negativa' approach from theology: when a political decision is subject of much controversy and conflicting interests, sometimes knowing what not to do is more important than what to do since abandoning unfruitful pathways makes more resources available to search for plausible ones. We argue that this approach works well in a debated field such as bioenergy sustainability governance and that it might be more relevant to avoid damages by identifying harmful options, rather than finding difficult agreements on what would be the 'best' option.

By highlighting lose-lose pathways we can support policy makers in avoiding undesirable options leading to unsustainable bioenergy. We did this by comparing our findings against the recently published package of measures to implement the European Green Deal. We found that, at European level, the proposed measures address most of the lose-lose options in our analysis. However, further scrutiny should be dedicated to test the effectiveness of these measures at national scale and on imported goods, especially for wood deriving from plantations recently established on primary and semi-natural forests.

The measures proposed in Table 2 are certainly not exhaustive as they refer only to the specific pathways analysed in this study. Further, additional policy measures, such as instituting an overall cap on the use of forest bioenergy or restricting the use of certain feedstocks, are not considered here because outside the scope of our analysis (i.e. focusing on a product-perspective and not on scales of deployment of bioenergy), but should be investigated further [164]. Similarly, the proposed more ambitious targets for net LULUCF emissions and removals [165] will represent an important driver for maintaining and enhancing forest C-stocks and sinks. While this greater ambition should in principle stimulate a climate-smart use of wood, such as aimed at long-lived wood products [166], the extent to which this might effectively support the development of win-win pathways for both climate and biodiversity is outside the scope of the present analysis.

In the spirit of adaptive governance, thus, these measures should be constantly tested, updated, and expanded, and scientists could play a crucial role in supporting the political process by continuing to refine the boundaries of the problem [171] and investigating the following research lines:

- More empirical research is needed to collect data on the impacts of various forest management practices on ecosystem condition and biodiversity attributes, as well as synthesis efforts to translate these findings across disciplines. Efforts in this direction are already ongoing, for instance this is one of the goals of the European Commission's Knowledge Centre for Biodiversity.[6]
- The impacts assessed in this study are based on a 'ceteris paribus' perspective, which is appropriate to capture only small-scale changes and is not suitable to capture the overall impact of large-scale deployment of bioenergy, because the study excludes market-mediated effects on other sectors [23]. Many holistic assessments of the potential role of bioenergy in climate change mitigation strategies are present in the literature [12]. We invite researchers to expand large-scale systemic assessments to go beyond carbon accounting and include more impact indicators for biodiversity and ecosystem condition. While quantitative methods for biodiversity impact assessment are still being developed, the common approach of using forest cover changes as proxies for biodiversity impacts is not sufficient [46]. Changes in forest management practices can have significant impacts on ecosystems, which might be overlooked by using only land-use proxies. A suggested list of relevant attributes and indicators for quantifying impacts on ecosystem condition is available in the MAES EU wide ecosystem condition assessment [26]. Aggregation methodologies for these indicators could be developed to produce a more synthetic quantitative indicator of impacts on ecosystems.
- Large-scale integrated assessments are important to highlight impacts across sectorial, geographical and temporal scales which are crucial for strategic policy choices [42,167]. However, to contrast the polarization of the debate surrounding bioenergy sustainability we recommend an approach of awareness and epistemic humility [168]. In section 2.3 we apply this approach by explicitly stating the framing of this work, including the principal worldview driving the study and influencing the value-laden assumptions chosen. By making clear that our results are conditional to the epistemic framing adopted for the assessment, the assumptions and limitations themselves become a source of useful knowledge for policy makers in exploring the solution space.
- Concerning the assessment of impacts on biodiversity, we suggest future research to investigate additional interventions (e.g. thinning operations, harvesting of unmanaged stands, agroforestry establishment, coppice conversion or restoration, salvage operations), as well as additional attributes (e.g. impacts on physical soil properties and water regulation), and to quantify the potential amounts of bioenergy that could be produced through the identified win-win pathways.
- Our assessment is based on synthesis rather than on specific case studies. However, local biotic, abiotic, and climatic conditions play an essential role when it comes to assessing potential impacts of forest bioenergy on biodiversity and climate change. For this reason, we suggest future research to look at case studies on smaller spatial scales, which could help decision makers in promoting win-win pathways at local scale (see for instance Fingerman and Carman [169]).

[6] https://knowledge4policy.ec.europa.eu/biodiversity_en.

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Definitions

Definitions are provided in Table S1.appsec1

Credit author statement

J. Giuntoli: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **J.I. Barredo:** Conceptualization, Methodology, Writing – original draft. **V. Avitabile:** Writing – review & editing. **A. Camia:** Conceptualization, Writing – review & editing, Project administration. **N. E. Cazzaniga:** Writing – review & editing. **G. Grassi:** Conceptualization, Writing – review & editing. **G. Jasinevičius:** Writing – review & editing. **R. Jonsson:** Writing – review & editing. **L. Marelli:** Writing – review & editing. **N. Robert:** Visualization, Writing – review & editing. **A. Agostini:** Methodology, Writing – review & editing. **S. Mubareka:** Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112180.

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